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Spectroscopy of $^{65,67}_{25}$Mn: Strong coupling in the $N = 40$ "island of inversion"

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A B S T R A C T

Excited states in ^{63,65,67}Mn were studied via in-beam γ-ray spectroscopy following knockout reactions from ^{68}Fe. Similar level schemes, consisting of the $11/2^-$, $9/2^-$, $7/2^-$ and $5/2^-_{g.s.}$ level sequence, connected by $I \rightarrow I-1$ transitions, were established, the first time for ^{65,67}Mn. Their level structures show features consistent with strongly-coupled rotational bands with $K = 5/2$. State-of-the-art shell-model calculations with the modified LNPS effective interaction reproduce the observed levels remarkably

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well and suggest the dominance of 4-particle-4-hole neutron configurations for all the states. The data on the low-lying excited states of odd-mass $^{53-67}$Mn provide a textbook example of nuclear structure evolution from weak coupling through decoupling to strong coupling along a single isotopic chain on the n-rich side of the β stability line. These results help to deepen our understanding of the $N = 40$ "island of inversion".

1. Introduction

With the acquisition of experimental data on nuclei far from stability in the last decades, the paradigm of universal shell structure has been abandoned [1,2], and much progress has been made by investigating the mechanism of shell evolution. At the $N = 40$ harmonic oscillator shell closure, ^{68}Ni has the appearance of doubly magic based on the high 2_1^+ energy [3] and low transition probability to the ground state [4,5]. However, the strength of this $N = 40$ shell closure was later proved to be unexpectedly weak by mass measurements [6,7]. While its ground state is still dominated by the normal fp configuration of a spherical shape [8–10], well deformed structures that become the ground state of lighter $N \sim 40$ nuclei have been observed recently, especially in Fe and Cr isotopes [11–17]. The experimental results available for these nuclei have been interpreted within the shell model framework in a large model space that includes the key orbitals, $\nu 1g_{9/2}$ and $\nu 2d_{5/2}$, for the development of quadrupole deformation [19]. Similar to the neutron-rich region around $N = 20$, where the ground state wave functions are dominated by intruder configurations, this area has been described as a new "island of inversion" [14,18, 19]. Indeed, the occurrence of intruder deformed configurations is attributed to both monopole effects due to the migration of neutron single-particle states as protons are removed from the $\pi 1f_{7/2}$ orbital [20,21] and multipole effects that favor quadrupole correlations in this valence space [19,22].

The collective properties in this region were obtained mainly from the study of even-even nuclei, while spectroscopic information on the odd-mass nuclei is still scarce due to the higher level density and the diversity of level structures even at low excitation energies. Compared with the relatively simple response of even-even nuclei to the development of collectivity, e.g., the decrease of the 2_1^+ energy and the increase of the $E(4_1^+)/E(2_1^+)$ ratio, the level structure of an odd-mass nucleus is sensitive to both the deformation of the underlying even-even core and the configuration of the unpaired nucleon [23]. Odd-mass nuclei therefore provide key additional insights into the nuclear structure evolution. Depending on the shape of the core and the strength of the Coriolis interaction [24], level and decay patterns corresponding to three distinct coupling-scheme limits can be recognized: weak coupling, decoupling and strong coupling [25]. For example at $Z = 27$, where the even-N Co isotopes have been studied up to $A = 67$, the low-lying states in odd-A Co isotopes can be understood in terms of weak coupling, indicating the dominance of single particle excitations around the semi-magic Ni isotopes [26]. On the other hand, the observation of deformed structures at low excitation energy in ^{67}Co implies the proximity to the edge of the "island of inversion" around $N = 40$.

Lying in between Cr and Fe, Mn isotopes are expected to be well deformed around $N = 40$, so it is very intriguing and challenging to reveal the particle-core coupling mode in these odd-mass Mn isotopes. Comprehensive investigations of the excited states in Mn isotopes with $N < 40$ have been carried out in various experiments. High-spin states in $^{57-60}$Mn have been studied using fusion-evaporation reactions [27]. In-beam γ spectroscopy of $^{59-63}$Mn has been carried out via multi-nucleon transfer reactions [28]. Recently, excited states up to $11/2^-$ in ^{63}Mn have been established in the fragmentation of ^{65}Fe [29], and ground state properties of $^{53-63}$Mn have been determined by laser spectroscopy at ISOLDE [30–32]. So far, except an unassigned 272 keV γ-ray observed in ^{65}Mn [33], in-beam γ spectroscopy of Mn isotopes with $N \geq 40$ has been out of experimental reach. In this Letter, we report on the first observation of excited states in ^{65,67}Mn and the confirmation of the ^{63}Mn result reported recently [29]. The level structures of ^{65,67}Mn display features of strongly-coupled rotational bands expected for well deformed odd-A nuclei. The nuclear structure evolution along the Mn isotopic chain ($N = 28$–42) from weak coupling through decoupling to strong coupling are discussed. In addition, as key isotopes in Urca cycle that cools the neutron star crusts via neutrino cooling [34], information on the low-lying levels of ^{63,65}Mn are of importance in deducing the electron capture and β-decay rates for the ^{63}Fe $\leftrightarrow$ ^{63}Mn and ^{65}Fe $\leftrightarrow$ ^{65}Mn Urca pairs [34].

2. Experiment and results

The experiment was performed at the Radioactive Isotope Beam Factory (RIBF), operated by the RIKEN Nishina Center and the Center for Nuclear Study of the University of Tokyo. A 15 pnA ^{238}U primary beam, accelerated to 345 MeV/u, was impinged on a 3-mm-thick ^{9}Be primary target for the production of secondary radioactive isotope beams via in-flight fission reactions at the entrance of the BigRIPS separator [35]. The isotopes of interest were selected and separated from intense secondary beams through the $B\rho$–ΔE–$B\rho$ method [36], and then impinged on a 102(1)-mm-thick liquid hydrogen (LH_2) secondary target at an incident energy of about 260 MeV/u. The secondary reaction residues were produced via proton-induced knockout reactions. The particle identification before and after the LH_2 target was performed unambiguously by the $B\rho$–ΔE–ToF method event-by-event in the BigRIPS and ZeroDegree spectrometer [36], respectively. The Time-Projection Chamber (TPC) of the MINOS device [37] surrounding the LH_2 target was used to reconstruct the vertex of the knockout reactions by tracking the emitted protons [38]. The γ rays emitted in-flight were measured by the DALI2 γ-ray spectrometer [39] surrounding the MINOS device. The setup is identical to previous experiments at the RIBF [17,40–45].

In the present work, excited states of ^{63,65,67}Mn were populated by the fragmentation of ^{68}Fe via the ^{68}Fe$(p, 2pxn)^{67-x}$Mn reaction channels, with $x = 4$, 2 and 0, respectively. The Doppler-corrected γ-ray spectra are displayed in Fig. 1, where the response functions of DALI2 were simulated with the GEANT4 framework [46] and the background was composed of two Landau functions. Three transitions were identified in the singles spectrum for each isotope. The information on the observed γ-transitions is summarized in Table 1. The effect on transition energy of the lifetime for the initial state has been evaluated and found to be negligible. The level schemes, displayed in Fig. 2, were established based on the γ–γ coincidence relationships and the relative intensities from both the singles and coincidence spectra. The spin-parity as-

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